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# General aspects, hierarchical controls and droop methods in microgrids: A review

Estefanía Planas [a,*], Asier Gil-de-Muro [b], Jon Andreu [a], Iñigo Kortabarria [a], Iñigo Martínez de Alegría [a]

[a] Department of Electronic Technology, University of the Basque Country, UPV/EHU, 48013 Bilbao, Spain
[b] Energy Unit, Tecnalia, Parque Tecnológico de Bizkaia, 48160 Derio, Spain

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ABSTRACT

Distributed generation is emerging as a new technology for supplying the increasing demand for electricity. Microgrids are attracting a great deal of attention since they integrate distributed generation in the main grid reliably and cleanly. When designing the control system of a microgrid, several functions must be considered, such as the management of electrical and thermal energy, load management, synchronisation with the main grid, etc. Both companies and institutions have carried out research into the control of microgrids over recent years and many proposals can be found in the literature. Thus, the design of the control system of a microgrid is a complex task due to its multiple functions and the large number of proposed solutions. This paper presents a complete description of the main features of a microgrid and describes the characteristics of the control systems used. Details are provided of the control tasks involved and of the main types of controls proposed in the literature. In addition, this paper describes the controls used in existing microgrids all over the world and proposes future areas for research.



**Contents**



## 1. Introduction

Energy policies have been conditioned by a number of factors such as environmental concerns, the intense growth of emerging

* Corresponding author. Tel.: +34 94601 7243.
*E-mail address:* estefania.planas@ehu.es (E. Planas).

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countries and the liberalisation of the energy sector in Europe. Distributed energy resources (DERs) are considered by most governments, the scientific community, etc., as the main candidates to cover future demand, reducing environmental impact in comparison with traditional energy sources such as coal, heating oil, etc. Thus, the presence of DERs in the grid has increased greatly over recent years and new concepts have been developed in order to integrate these, guaranteeing the satisfactory operation of the main grid. Among these new concepts, of special interest is the virtual power plant (VPP), which was developed to enhance the visibility and control of DERs to system operators and other market players by providing an appropriate interface between these system components [1].

The generation of electricity based on DERs is an efficient, reliable and environmentally friendly alternative to the traditional centralised energy system [2]. This is due to several factors, such as smaller generators, the shorter distance between the generators and loads, higher use of renewable energies, etc. However, because of their intermittence, randomness and the uncertainty caused by meteorological factors, it is difficult to integrate renewable energy sources directly into the utility grid. By integrating distributed and renewable sources, energy storage devices, a variety of loads, data acquisition and supervisory control devices, microgrids are the interface between the distributed renewable sources and the utility grid (Fig. 1) [3]. Microgrids can be defined as small, local distribution systems containing generation and load, the operation of which can be separated totally from the main distribution system or connected to it [4], differing from existing island power systems (such as offshore oil/gas platforms, ships, etc.) in which the connection to and disconnection from the main grid is a regular event [5]. A microgrid can be disconnected from the main grid when it fails or when its power quality is not satisfactory [6] and users can obtain a higher quality supply and a cheaper and cleaner form of power if economic and emission policies are considered.

Microgrids have several features that make them differ from conventional power systems: (a) the steady-state and dynamic characteristics of DERs are different; (b) there is a significant degree of imbalance due to the presence of single-phase loads and/or DERs, and (c) there is a considerable portion of supply from "noncontrollable" sources, etc., which cause the required control strategies to differ from those of conventional power

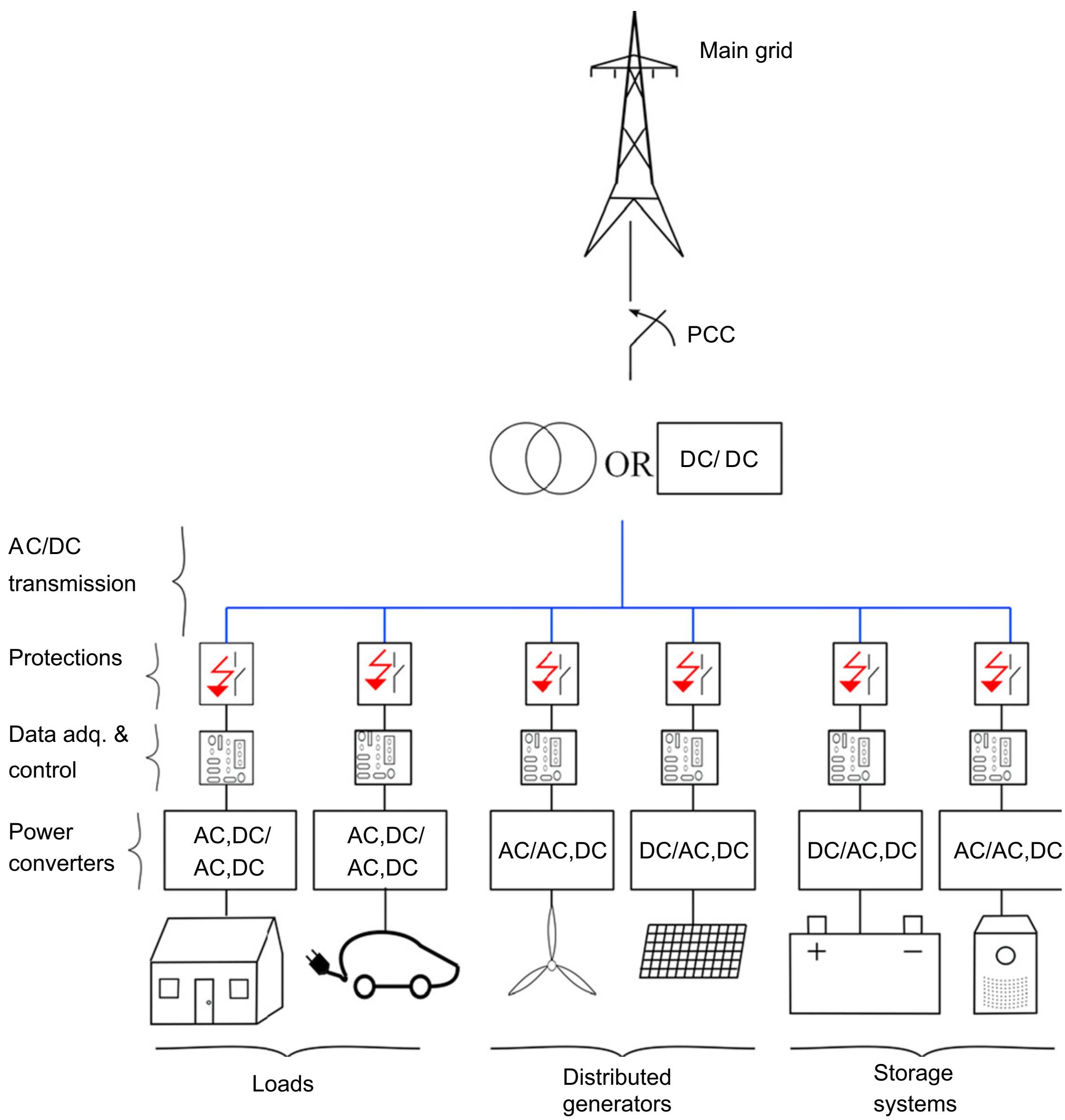



Fig. 1. A general scheme of a microgrid.

systems [7]. Likewise, microgrids must guarantee a number of different functions, such as the supply of electrical and/or thermal energy, participation in the energy market, etc. Several companies and institutions have developed a large number of control systems [5,8–16] in order to satisfy all the functions required of a microgrid. Therefore, a large amount of literature concerning several different aspects of microgrids is available. Thus, the design of the control system of a microgrid is a complex task that involves a range of different functions that can be carried out in many different ways.

This paper presents an overview of the many different aspects of microgrids. It sets out the characteristics of a microgrid control system and presents the main control techniques proposed in the literature. In addition, information is provided on the research projects on microgrids and experimental microgrids currently underway all around the world. Finally, the paper provides a number of examples of islanded microgrids and proposes future areas of research.

## 2. Description of a microgrid

### 2.1. Structure

Microgrids are integrated systems in which DERs operate in the form of a grid that can be connected to or disconnected from the main grid at the point of common coupling (PCC) (Fig. 1). The elements that form a microgrid are described as follows:

- *Distributed generators* (*DG*). Electric microgrids are a good option for integrating different types of DGs since they exploit the available resources in each location (wind, sun, biomass, etc.) (Fig. 1). DGs can operate in two ways: as current or power sources, in accordance with power regulations or as voltage sources, establishing the voltage and frequency of the microgrid. For current sources, the main strategies are divided in linear controllers and nonlinear controllers [17]. When the power converters operate as voltage sources, the control is usually based on a voltage loop cascaded with an inner power loop [18].
- *Storage systems* (*SS*) (Fig. 1). Stability, power quality, and reliability of supply are improved thanks to the use of energy storage technologies [19]. Moreover, they enhance the overall performance of microgrid systems in three ways [20]: DGs can run at a constant and stable output or can optimally follow the control reference despite load fluctuations, they provide a ride-through capability when there are dynamic variations in primary energy and they permit DGs to operate seamlessly as dispatchable units. In [21] a review of the advancement of microgrid oriented energy storage technologies can be found.
- *Loads*. Microgrids can supply electrical energy to different kinds of loads (residential, industrial, etc.) (Fig. 1). These loads are classified as critical/sensitive and noncritical loads in order to achieve the desired operation [22]. This operation includes aspects like priority service to critical loads, power quality enhancement of specific loads, reliability improvement of prespecified load categories, etc. Local generation with fast and accurate protection systems can prevent disturbances from affecting sensitive loads [23].

### 2.2. AC microgrids vs DC microgrids

In accordance with the type of distribution (Fig. 1), there are alternating current (AC), direct current (DC) and mixed AC/DC microgrids. Almost all the experimental microgrids implemented all over the world use an AC distribution system [22]. In general, AC distribution presents a number of advantages over DC distribution systems [24]:

- *Voltage transformation*. AC voltage can be incremented and decremented easily through the use of electrical transformers. On the other hand, DC voltage conversion is made by means of DC–DC converters which require a more complex implementation.
- *Circuit breaker protection*. Circuit protection is more mature for AC systems than for DC systems and more research is required into DC systems.

However, DC distribution systems also offer several advantages in comparison with AC distribution systems [23–26]:

- *Incorporation of renewable energy resources*. Batteries, PVs, etc. can be easily connected to DC distribution systems without the need for inversion stages.
- *Higher reliability*. DC lines present lower impedance than AC lines. In addition, the skin effect is only present in AC systems, which increases the thickness of the AC lines.
- *Nonreactive load*. Nonreactive power is present in DC lines. Thanks to this, the power transfer capacity increases and greater use is made of the capacity of the generators.
- *No need for synchronisation*. DC systems have zero frequency, thus no synchronisation control is needed in order to connect or disconnect devices to the grid.
- *Connecting loads*. A large number of loads (PCs, battery chargers, etc.) incorporate voltage rectification stages to connect them to the common AC grid. If a DC distribution line is used, these rectification stages are avoided and only smaller DC–DC conversion stages are needed.
- *Avoid human exposure to* 50/60 *Hz*. The potential health concerns from human exposure to 50/60 Hz are avoided when DC distribution lines are adopted.

Moreover, statistical operational data used to compare AC and DC systems for critical loads show that the availability of DC architectures is higher [25]. The low voltage (LV) DC microgrid is most suitable in applications in which most of the loads are sensitive electronic equipment and these have been used in telecom power systems, power-system control and protection systems [27]. Although the presence of DC microgrids is still limited, the interest of the scientific community is increasing thanks to the advantages they offer.

### 2.3. Standards

Over recent decades, several companies and institutions have developed multiple devices and controls in order to integrate these DERs into the main grid in a suitable manner. Therefore, many varieties of controls, interconnections, electronic interfaces, etc. can be found, hindering the design of a unique standard for connecting DERs to the grid. A number of standards have been developed, one of the most important being the *IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems*1547 [28]. This family standard is being developing by the IEEE Standards Coordinating Committee 21 and establishes criteria and requirements for the interconnection of distributed resources with electric power systems. Although no specific standard has been developed to deal with microgrids, some of the existing standards for DERs can be adapted to them. Specifically, section 1547.4 is being treated as the fundamental standard for microgrid standardisation as it covers planning and operating aspects such as the impacts of voltage, frequency, power quality, protection schemes and modifications, the characteristics of DERs,

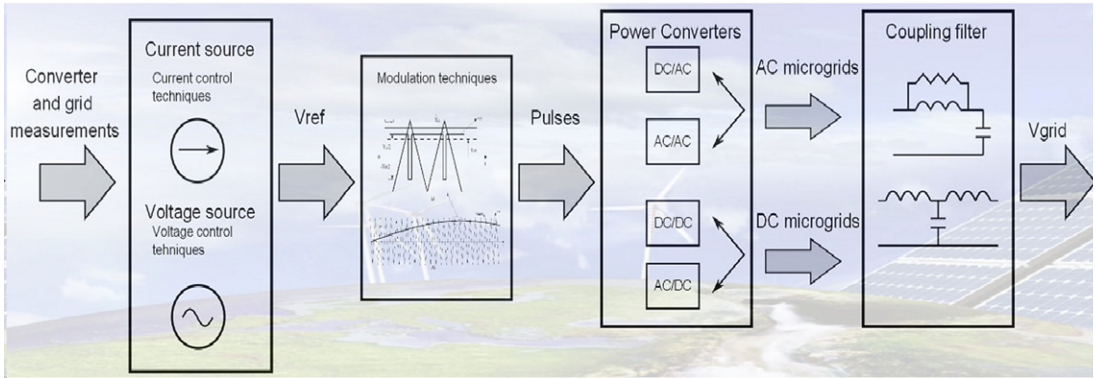



**Fig. 2.** Inner control of power converters in DC and AC microgrids.

**Table 1**
Applicable standards to microgrids.

| Standard | Description | Scopes |
|---|---|---|
| IEEE 1547 | Criteria and requirements for interconnection of DERs with the main grid | ▶ 1547.1 Conformance test<br>▶ 1547.2. Application guide<br>▶ 1547.3. Monitoring and control<br>▶ 1547.4. Design, operation and integration of DERs<br>▶ 1547.5. Interconnection guidelines for electric power sources greater than 10 MVA<br>▶ 1547.6. Interconnection with distribution secondary networks<br>▶ 1547.7. Distribution impact studies for interconnection of DERs<br>▶ 1547.8. Recommended practice for establishing methods and procedures |
| EN 50160 | Voltage characteristics of electricity supplied by public distribution networks | ▶ Definitions and indicative values for a number of power quality phenomena in LV and MV networks<br>▶ Limits for power frequency, voltage variations, harmonics voltage, voltage unbalance, flicker and mains signalling |
| IEC 61000 | General conditions or rules necessary for achieving electromagnetic compatibility | ▶ Safety function and integrity requirements<br>▶ Compatibility levels<br>▶ Emission and immunity limits<br>▶ Measurement and testing techniques<br>▶ Installation guidelines, mitigation methods and devices |
| IEEE C37.95 | Protective relaying of utility-consumer interconnections | ▶ Establishment of consumer service requirements and supply methods<br>▶ Protection system design considerations |
| IEEE 37.118 | IEEE Standard for Synchrophasors for Power Systems | ▶ Definition of a synchronised phasor<br>▶ Time synchronisation, application of time tags<br>▶ Method to verify measurement compliance with the standard<br>▶ Message formats for communication with a PMU |

reserve margins, and load shedding [29]. In Europe, some of the existing standards, such as EN 50160 and the IEC 61000, can be also adapted to microgrids [30]. Table 1 presents a summary of the European and American standards applicable to microgrids.

### 2.4. Protection in microgrids

Protection schemes and devices are another important issue in microgrids. In general, a protection system consists of protection devices, protective relays, measurement equipments, and grounding [27]. Protection issues in microgrids can be divided in two groups according to the microgrid operating state (grid-connected and islanded modes) and traditional protection schemes must be adapted to microgrids for several reasons [29]:

- Different fault current levels and direction. Microgrids can work both connected and disconnected to and from the main grid. Currents can work in both directions and protections must take both directions into consideration. Fault current levels also change from traditional layouts since the power range of the generators are lower and current fault limits must be adapted to these levels.
- Dynamic structure of microgrids. The layout of a microgrid can change at any moment since the DGs and loads can be connected or disconnected at any instant. These changes in electrical layout have to be considered since the direction and limits of the currents circulating in the microgrid are modified. The grounding of the microgrid has to be also designed considering that the microgrid can operate both connected and disconnected from the main grid.

For all these reasons, new protection solutions must be provided in order to guarantee the proper operation of the microgrid. A possible solution for the protection of LV microgrids is to divide this into several zones with different types of devices in order to configure a suitable protection scheme [31]. Other protection solutions can be found in [32–34].

On the other hand, it must be remembered that DC microgrid protection faces the challenges posed by the lack of standards, guidelines and practical experience [35]. However, nowadays,

there are several protection devices available on the market for LV DC systems, that comprehend fuses, circuit breakers (CBs), molded-case circuit breakers (MCCB), LV power CBs, and isolated-case CBs. Some examples of commercially available protection devices for LV DC systems are listed in Table 2 [27]. Mixed microgrids with AC and DC distribution parts must also be considered. In these cases, the system can be divided in three parts: the main grid, the AC microgrid and the DC microgrid. A DC protection system is designed for the DC microgrid and a AC protection system for the AC microgrid [27]. The nature of load is also very important for stable operation of microgrid and detailed study of faulty situation in the presence of all possible types of load is essential for satisfactory operation of microgrid [36].

## 3. Hierarchical control of microgrids

The control system of a microgrid has several functions: load sharing between DGs, power quality, participation in the energy market, provision of ancillary services, etc. These objectives can be achieved through a hierarchical scheme control of three levels. These levels are described from the outer to the inner level of control as follows [7]:

- *Grid level*. At this level, a distribution network operator (DNO) and a market operator (MO) are found. The main functions carried out at this level are:
  - Responsibility for managing the operation of the medium voltage (MV) and LV areas with several microgrids.
  - DNO interface with several microgrid central controllers (MGCC).
  - One or more MOs in the system when the microgrid operates on the market.

**Table 2**
Examples of commercially available protection devices for LV DC systems.

| Type | Manufacturer | $U_n$ (V) | $I_n$ (A) | $I_{sc}$ (kA) |
|---|---|---|---|---|
| Fuse | Ferraz Shawmut | 500–1000 | 1–600 | 100 |
| Fuse | IFO electric | 250–550 | 2–630 | 120 |
| MCCB | ABB | 250–750 | 25–800 | 16–70 |
| MCCB | Eaton | 250–750 | 15–630 | 10–42 |
| MCCB | Siemens | 250–600 | 26–630 | 20–32 |
| CB | Sacheron | 900–3600 | 1000–6000 | 80 |

- *Management level*. A MGCC guarantees the following tasks:
  - Restoration control, which improves the frequency and voltage of the microgrid.
  - Synchronism between the microgrid and the grid. The main synchronisation methods are classified in zero-crossing methods, filtering of grid voltages and phase-locked loop (PLL) techniques [18].
  - Loads to be served or shed.
  - Optimisation of the production of the microgrid taking into account factors like the market prices for electricity and gas, grid security and the optimisation of local production capabilities.
- *Field level*. Local controllers (LCs) carry out the following functions:
  - Inner control of DERs for meeting voltage and frequency references (Fig. 2).
  - Load and microsource controls.
  - Power generation control, working in current and voltage modes and guaranteeing the satisfactory performance of the system.
  - Islanding detection, being capable of working both when connected and disconnected to and from the main grid.

The two entities, DNO and MO, are in charge of the microgrid and their main interface with the microgrid is the MGCC. The MGCC assumes different functions such as maximising the production of the microgrid, coordination of LCs, etc. On the other hand, it must be remembered that microgrids can be interconnected, forming an MV network. In this case, an intermediate management control structure is added to carry out some management tasks [37].

Of the three levels that make up this hierarchy, the field level has been studied in depth in the literature. In this way, the local control of the DERs has three main functions, as can be seen in Table 3. These three functions are detailed as follows:

- *Inner control of the DERs*. This control depends mainly on the type of source controlled. In this way, the automatic voltage regulator (AVR), pitch control of the turbine, etc. are some of the existing controls for controllable sources. In the case of noncontrollable sources, maximum power point tracking (MPPT) algorithms can be highlighted among the existing techniques. For SS units, the choice of the type of control (Table 3) will depend on whether they are for long term or short term storage.
- *Power generation control*. DERs can work when disconnected or connected from and to the grid. When they work connected to

**Table 3**
Local control functions and controls.

| Function | Classification | Control |
|---|---|---|
| Inner control of the DERs | Controllable sources | ▶ AVR and governor control |
| | | ▶ Stall or pitch control of turbine |
| | Renewable sources | ▶ Turbine speed and voltage controls |
| | | ▶ MPPT and voltage controls |
| | Long term storage | ▶ State of charge and output, voltage/frequency controls |
| | Short term storage | ▶ State of charge, speed control |
| Power generation control | Autonomous mode | ▶ Based on communications |
| | | ▶ **Droop methods** |
| | Grid connected mode | ▶ Power export (with/without MPPT) |
| | | ▶ Power dispatch, real and reactive power support |
| Islanding detection | Active methods | ▶ Based on current injection |
| | | ▶ Sandia National Laboratories algorithm |
| | Passive methods | ▶ Under/over voltage and under/over frequency algorithms |
| | | ▶ Phase jump algorithms |
| | Utility level methods | ▶ Based on communication signals |
| | | ▶ SCADA |

the grid, real and reactive generated powers are controlled. In the case of several DERs working autonomously, some form of control is needed in order to avoid circulating currents between them and to establish the voltage and frequency of the formed grid. The proposed controls are classified basically in communications based techniques and droop methods (Table 3).

- *Islanding detection methods*. DERs continue providing energy to the isolated section in both planned or unplanned islanding. The main islanding detection algorithms are classified as passive, active and utility level algorithms (Table 3) [38].

The microgrid concept of the Consortium for Electrical Reliability Technology Solutions (CERTS) establishes that a key element of the control design of microgrids is that communication among microsources is unnecessary for basic microgrid operation [39]. In this way, each microgrid controller must be able to respond effectively to system changes without requiring data from other sources or locations. Droop methods are presented as wireless control techniques that satisfy this characteristic. Apart from this, many publications suggest that droop methods are the best option for controlling DERs in microgrids [7,9,10,29,39]. Moreover, almost all the experimental microgrids implemented use droop methods [22]. In order to analyse these control methods more deeply, a study of droop methods is presented in the following section.

### 3.1. Droop methods

Droop methods are based on the behaviour of synchronous generators. The equivalent circuit of a synchronous generator connected to the grid is presented in Fig. 3. The real power injected into the grid can be expressed as

$$S=P+jQ, \tag{1}$$

where $P$ and $Q$ are the active and reactive powers. An impedance, $Z_\theta$, is shown between the grid and the generator in Fig. 3. This impedance is formed by the synchronous or internal impedance of the generator and the line impedance existing between the generator and the grid. On the one hand, the internal impedance presents a mainly inductive behaviour. Moreover,

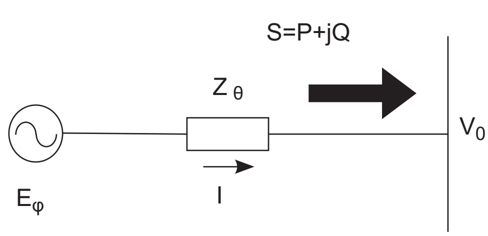



**Fig. 3.** Synchronous generator connected to an AC bus.

these generators are usually connected to high voltage lines, which are also mainly inductive. Consequently, the impedance of the equivalent circuit is considered inductive and the active and reactive powers can be described as follows:

$$P=\frac{EV}{X}\sin\phi, \tag{2}$$

$$Q=\frac{EV\cos\phi-V^2}{X}. \tag{3}$$

From (2) and (3), taking into consideration small phase differences between $E$ and $V$ ($\sin\phi\approx\phi$ and $\cos\phi\approx 1$), it is observed that $P$ and $Q$ depend mainly on $\phi$ and $E$–$V$, respectively. In this way, $P$ and $Q$ can be controlled by means of the phase and amplitude of the output voltage, respectively. Consequently, thanks to the fact that the inductive behaviour of the synchronous impedance $P$ and $Q$ influences the voltage and frequency of the generated voltage, respectively and benefits synchronous behaviour when two or more generators work in parallel. Taking all these factors into account, the reproduction of this behaviour in power converters is proposed in [40]. The simplest way of reproducing this behaviour in the power converters is to add the following characteristics (Fig. 4) [40]:

$$\omega^* = \omega_0 - m_i * (P_i - P_{oi}), \tag{4}$$

$$E^* = E_0 - n_i * (Q_i - Q_{oi}), \tag{5}$$

where $i$ is the index representing each converter, $\omega_0$ and $E_0$ are the nominal frequency and voltage of the voltage system, $P_i$ and $Q_i$ are the actual active and reactive powers and $P_{oi}$ and $Q_{oi}$ are the nominal active and reactive powers. On the other hand, different ranges of power are usually found when paralleling several converters. The following droop slopes make each converter generate according to its power range (Fig. 4) [40]:

$$m_1 P_{range1} = m_2 P_{range2} = \cdots = m_n P_{rangen}, \tag{6}$$

$$n_1 Q_{range1} = n_2 Q_{range2} = \cdots = n_n Q_{rangen}, \tag{7}$$

where $P$, $Q_{range1,2\ldots n}$ refer to the active and reactive power ranges in which the power converters operate.

The main advantages [41–43] and drawbacks [43–45] of the original droop method are presented in Table 4. Moreover, variations in the proposed droop method made in order to overcome the main disadvantages of the original droop method are shown in the same table. These proposed variations are:

- *Load sharing and voltage and frequency regulation trade-off*. One of the drawbacks described in Table 4 is the inherent trade-off of the droop method between voltage regulation and load sharing. The main solutions proposed can be classified in restoration controls [8,41], dynamic slopes [46,47] and high gain angle droop control instead of frequency droop control [48].

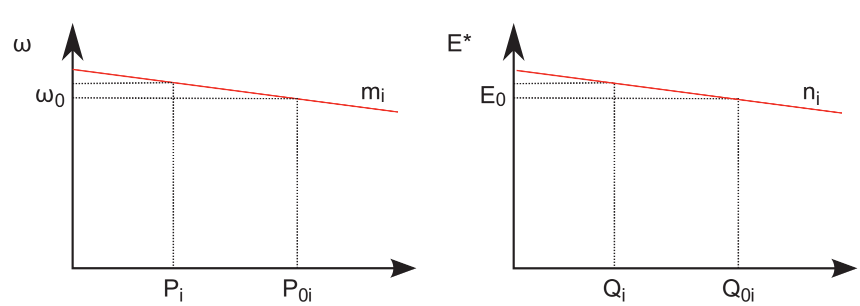



**Fig. 4.** Droop characteristics of frequency and voltage.

**Table 4**
Main advantages and disadvantages of the classic droop method and its variations.

| Advantages | Drawbacks | Proposed solutions |
|---|---|---|
| √ Avoid of communications | × Trade-off between voltage regulation and load sharing | ⋆ Restoration control<br>⋆ Dynamic slopes<br>⋆ High gain order slopes with supplementary loop |
| √ Great flexibility | × Poor harmonic sharing | ⋆ Additional loop for the bandwidth<br>⋆ Injection of an AC signal<br>⋆ Virtual impedance<br>⋆ Harmonic droop coefficients<br>⋆ Cooperative harmonic filtering strategy |
| √ High reliability | × Coupling inductances | ⋆ Virtual impedance<br>⋆ Virtual impedance variations |
| √ Free laying | × Influence of system impedance | ⋆ Additional loop with grid impedance estimation<br>⋆ Voltage droop coefficients by output active and reactive powers<br>⋆ Reactive current additional loop<br>⋆ Voltage droop estimation |
| √ Different power ratings | × Slow dynamic response | ⋆ Angle droop<br>⋆ Adaptive decentralised droop<br>⋆ Droop based on coupling filter parameters<br>⋆ Droop based on $H_\infty$ control theory<br>⋆ Controllable droop slopes |
| | × Integration of renewable energies | ⋆ Nonlineal droop control<br>⋆ Hybrid MPPT with droop control |

- *Harmonic load sharing*. On the other hand, the original droop method guarantees good $P$ and $Q$ sharing but does not take into account harmonic load sharing in the case of nonlinear loads. The main proposals found in the literature are: addition of a loop that reduces the gain and bandwidth of the reference voltage in the presence of distorted components to the droop control in [49], injection of an AC signal [50], virtual impedance [44,51–55], harmonic droop coefficients [56] and cooperative harmonic filtering strategy [57,58].
- *Coupling inductances*. These components increase the size and weight of the system. These physical inductances can be replaced by a virtual impedance [51] and consecutive virtual impedance variations [44,53,54].
- *Line impedance*. The line impedance between the paralleled converters also affects the performance of the original droop method (Table 4). Several techniques have been proposed in order to overcome this drawback: additional loop with grid parameters estimation [59], voltage droop coefficient by means of output active and reactive powers [60], decoupling of $P$ and $Q$ [61], reactive current addition to the droop control loop [62] and estimation of the impedance voltage drops [63].
- *Dynamic response*. The original droop method presents a slow, oscillating dynamic response which is overcome in several proposed solutions: angle droop instead of frequency droop [64], adaptive decentralised droop [65], droop based on coupling filter parameters [66], droop based on $H_\infty$, derived from linear matrix inequality (LMI), control theory [67] and addition of derivative terms [68].
- *Integration of renewable energy resources*. Finally, the last drawback of the original droop method is its poor performance with renewable energy resources. In order to mitigate this, a nonlinear droop control is proposed in [69] and an hybrid maximum power point tracking (MPPT) with droop control in [70].

On the other hand, the hierarchical control described above can be carried out in a centralised or decentralised manner. The features of each control mode are explained in the following sections.

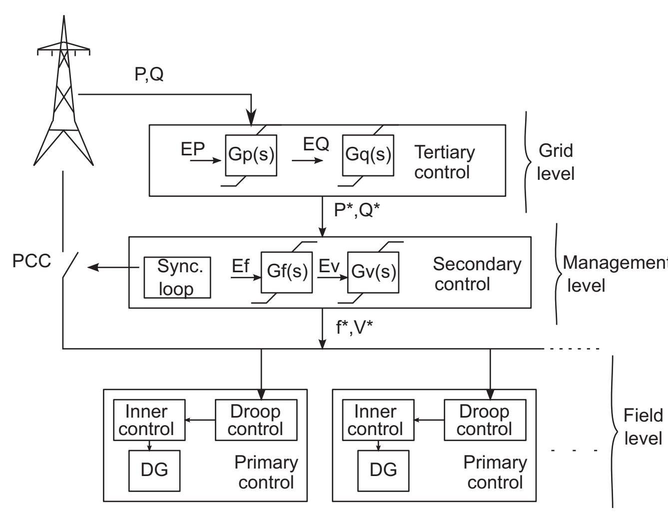



**Fig. 5.** Centralised hierarchical control of microgrids.

### 3.2. Centralised control of microgrids

Several publications have proposed a centralised hierarchical control for microgrids [7,8,71–73]. In this control, the different hierarchical control levels have several tasks [71]. At the grid level of the hierarchy a tertiary control is implemented. This control has the following tasks:

- Management of the importation or exportation of active and reactive powers to or from the grid.
- Estimation of the grid impedance in order to take it into account in the control.
- Nonplanned islanding detection.

The tertiary control calculates the desired active and reactive powers ($P^*$,$Q^*$, Fig. 5) and sends them to the management level of

the control. The management level corresponds to the secondary control, which is also responsible of the following tasks:

- Restoration of amplitude (EV) and frequency (Ef) deviations produced by the primary control in the field level (Fig. 5).
- Synchronisation loop (sync. loop in Fig. 5) in order to transfer the microgrid from islanding to grid-connected modes.

Likewise, the secondary control computes the desired values for frequency and voltage amplitude ($f^*$,$V^*$, Fig. 5) in the microgrid and sends them to the field level. Finally, the field level or primary control allows the connection of different loads, DGs and SSs. This primary control consists of the inner control (Table 3) and droop control explained in detail in Section 3.1.

### 3.3. Decentralised control of microgrids

In order to carry out the decentralised control of the microgrid, the agent-based control (MAS) was proposed in [74]. Later, several proposals have developed this concept [6,37,75–78].

This type of control sets out to provide the maximum autonomy for the DERs and loads within the microgrid by means of giving a certain degree of intelligence to the LCs. The LCs can communicate with one another to form a larger intelligent entity [7]. The MAS is also used for optimal voltage regulation in smart grids [79]. Software agents can be defined as software components able to communicate one with another in top level languages and to announce the services that they provide in a dynamic way [6]. Some of their basic characteristics are [74]:

- *Physical or virtual*. They can control a DER directly or they can be a piece of software that makes bids to the energy market or stores data in a database.
- *Influence on their environment*. Agents change their environment as a result of their actions since a change in one agent can cause changes in the other agents.
- *Communication with each other*. The agents can communicate with each other and can work in a coordinated way.
- *Certain level of autonomy*. They take decisions without a central controller or commander and they are driven by a set of tendencies.
- *Partial or no representation of the environment*. The agents know partially what happens in the system. Minimum data exchange and computational demands are attained in this way.
- *Different objectives for each agent*. Each agent has certain targets and satisfies these by means of its resources, skills and services.

On the other hand, a generic architecture for implementing a MAS system for microgrids has the following basic services [6]:

- *Registration and agent discovery*. The services that the agents provide are kept in a central register. Agents can be subscribed to this registry in order to receive notifications about new agents, disconnected agents, etc.
- *Messaging system*. The architecture is distributed into different hosts thanks to the messaging based on internet communications.
- *Agent platform management system*. This framework manages basic services such as the creation and deletion of agent containers and the agents themselves.

A decentralised hierarchical control based on the development of a communication overlay toolbox (Agora+) was also proposed in [80]. In this paper, the concept of autonomous electricity networks (AEN) is defined as a group of DERs in a real-time price market, capable of cooperation and control in a distributed manner. AEN is presented as an answer to the integration of a high penetration of small DERs in the electricity network operation.

### 3.4. Centralised and MAS decentralised controls: comparison

Considering the features of each control described above, it can be said that MAS decentralised controls have several advantages over centralised controls [6,74]:

- *The amount of information*. MAS technology provides each LC with information about its neighbour. However, in centralised controls it is very difficult for the MGCC to access all the information available.
- *Data communication infrastructure*. MAS systems use a local network and only essential data is exchanged. In order to obtain similar results, a centralised control requires a significant flow of data to a central point. In cases where real time functionalities are needed, the system would become more difficult and expensive.
- *Openness of the system. Plug & play* capability is achieved with a decentralised control. If a new DER is connected to the microgrid, a programmable agent in its control is provided without modifying the rest of the control. However, in centralised controls the MGCC has to be programmed when a new DER is connected.

However, decentralised controls have yet to attract the attention of the scientific community. There are two main factors that influence the interest of researchers in the centralised controls [81]:

- *Global perspective of the system*. Making decisions is easier when the information is collected in a central point.
- *Easy implementation*. Prioritisation and cooperation is achieved more easily from a central controller.

Therefore, it may be said that the centralised control is best used in cases when the owners of the microsources and loads have common goals and in cases of small-scale microgrids which can be controlled by an operator. On the other hand, a decentralised control can be best used in cases of microsources of different owners, microsources operating in a market environment and local microsources with other tasks besides supplying the local distribution networks (producing heat for local installations, etc.) [10].

Besides these advantages and disadvantages, it is interesting to make a comparison between the costs of installation and operation of the two control types. In Fig. 6 the general architecture of a hierarchical control for a microgrid formed by one DG, one load

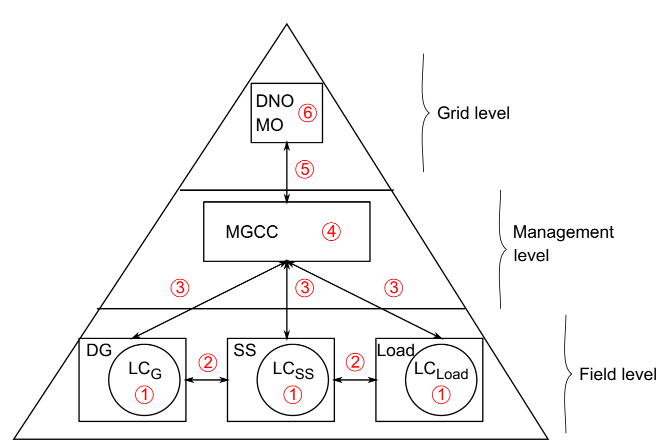



**Fig. 6.** General architecture of centralised and decentralised hierarchical controls of microgrids.

and one SS is presented. In this architecture, some elements have been raised (①–⑥) which characteristics change according to the selected control (centralised or decentralised). These characteristics are:

- *Complexity of the control* (Fig. 6, ①, ③ and ⑤). In the basic operation of the centralised control, local controllers (Fig. 6, ①) only guarantee load sharing and voltage and frequency regulation [71]. In the same manner, the MGCC (Fig. 6, ③) ensures nominal values of voltage and frequency on the microgrid and synchronisation with the main grid by means of low-bandwidth communications with the local controllers. Although, if more functionalities are added to the basic centralised control, its complexity gets higher, involving higher costs of design and implementation.
  In case of MAS control, besides the basic functions commented, local agents (Fig. 6, ①) have also knowledge about the specific device (DG, load, SS, etc.) they are controlling, take decisions about their behaviour and provide information accordingly to the MGCC [6]. Moreover, they receive control signals from the MGCC agents (Fig. 6, ③), but they have the final autonomy for executing the requested operation points. In addition, the MGCC agent, besides the basic functions, also manages all the information coming from the local agents and decides on the best operating set points for them, optimising the operation of the entire microgrid [6]. The design of the DNO and MO (Fig. 6, ⑤) can also involve more complexity for MAS control. All these additional functions increase highly the complexity of the MAS control. This complexity involves a control hardware suitable for high computational load and higher costs of design and implementation in comparison with the basic centralised control.
- *Communications* (Fig. 6, ②, ④ and ⑥). In the centralised control local controllers operate autonomously without communications between them (absence of ②, in Fig. 6) and they receive the operation points from the MGCC by means of low-bandwidth communications (Fig. 6) ④ [8]. It has to be also considered that, as more real-time functions are added to the centralised control, the complexity of its communication system increases, involving higher costs of design, installation and implementation.
  However, MAS architecture requires a fairly advanced communication system with capabilities similar to human speech [7] involving, for example, internet connections between all the agents presented in the three levels of hierarchy (Fig. 6, ②, ④ and ⑥) [6].
- *Fault tolerance* (Fig. 6, ①–⑥). The centralised control guarantees the load sharing in the microgrid in island mode even if the communications with the DNO, MO (Fig. 6, ⑤) or with the MGCC (Fig. 6, ③) fail or some of the LCs (Fig. 6, ①), the MGCC (Fig. 6, ④) or the DNO or MO (Fig. 6, ⑥) do not work properly. The reason for this is that the droop method in the field level (Fig. 5) ensures the load sharing without any connection between the DERs [7,9,10,29,39]. In this way, if the MGCC of the basic centralised control does not operate or its communications fail, the LCs continue working autonomously, but without the capacity of grid connection nor restoration of nominal values of frequency and voltage in the microgrid. In the same manner, if the DNO or MO or the corresponding communications fail, the microgrid is still able to work both connected and disconnected from the grid but loosing the capability of considering market's issues and other connected microgrids in its control.
  In case of MAS control, the fault tolerance of the architecture relies on the intelligence implemented in the agents. A good design of the MAS control can minimise the consequences of the failure of the communications or essential elements such as the central register.
- *Flexibility and modularity* (Fig. 6, ③ and ④). When new DERs are connected to a microgrid with a centralised management system, new connections are required between the new DERs and the MGCC (Fig. 6, ④) and the control algorithms of the MGCC must be adapted (Fig. 6, ③) [71].
  However, MAS control offers high performance *plug and play* capabilities and high levels of modularity and scalability. Altogether, these characteristics allow MAS control systems to be adapted rapidly and easily to different microgrids in terms of size, installed devices and control functions [6]. So, the costs related to modifications in the architecture of the microgrid are decreased when MAS control system is selected.

**Table 5**
Examples of microgrids in Europe.

| Situation | | Project manager | Type | | Control | | Structure | |
|---|---|---|---|---|---|---|---|---|
| Place | Country | | Real | Test-bed | Cent. | Decen. | AC | DC |
| Bornholm island | Denmark | More microgrids project | √ | | [a] | | √ | |
| Lyon | France | NEDO | | √ | [a] | | √ | |
| Kassel | Germany | The Institut für Solare Energieversorgungstechnik (ISET), University of Kassel Institute for Electrical Energy Technology (IEE) | | √ | √ | | √ | |
| Mannheim Wallstadt | Germany | More microgrids project | √ | | | √ | | |
| Stutensee | Germany | DISPOWER project | √ | | √ | | √ | |
| Atenas | Greece | National Technical University of Athens (NTUA) | | √ | | √ | √ | |
| Milan | Italy | Ricerca Sistema Energetico (RSE) | | √ | √ | | | √ |
| *Agria* pig farm | Macedonia | *More microgrids* project | √ | | [a] | | √ | |
| Bronsbergen | Netherlands | *More microgrids* project | √ | | √ | | √ | |
| Groningen | Netherlands | KEMA | √ | | | √ | √ | |
| Utsira | Norway | StatoilHydro and Enercon | √ | | √ | | √ | |
| Ilhavo | Portugal | *More microgrids* project | √ | | | | √ | |
| Barcelona | Spain | Institut de Recerca en Energia de Catalunya (IREC) | | √ | [a] | | √ | |
| Derio | Spain | *More microgrids* project | | √ | √ | √ | √ | |
| Miñano | Spain | Ikerlan | | √ | √ | | √ | |
| Horizon, Manchester | UK | H2Ope | √ | | [a] | | [a] | |
| Manchester | UK | University of Manchester | √ | | √ | | √ | |

[a] No data found.

Thus, it can be said that the centralised control offers the possibility of implementing a basic management system for the control of microgrids with low costs of installation and operation. However, if more advanced functions or real-time tasks are required, the complexity of the design increases and the MAS control starts to be more economical. Hence, initially the costs of installation and operation of a MAS control are higher, but they can be amortised as long as more advanced functions are added to the management system of the microgrid. In the same manner, MAS control offers a *plug and play* performance which involves lower costs related to modifications in the microgrid's architecture at the expense of a complex design of the control.

## 4. Microgrids all over the world

### 4.1. Microgrids nowadays

Microgrids are a good option in applications where the presence of energy must be guaranteed at all times (hospitals, servers, etc.). They are also interesting in cases in which the main grid is not robust due to factors such as the long distance from the main grid. In this way, in extensive, highly dispersed countries such as Canada, USA, Japan, etc., major efforts are being made into microgrid research. Organisms such as CERTS in US, Power System Engineering Research Center (PSERC) and British Columbia Institute of Technology (BCIT) in Canada and New Energy and Industrial Technology Development Organisation (NEDO) in Japan feature microgrids within their research programmes. In the USA, there are at least nine ongoing microgrid projects [82] and several microgrid projects are also being carried out in Australia [83]. In Europe, research efforts in the field of microgrids have taken the form of the *Microgrids* project and the following *More microgrids* projects. The first project was carried out with the aim of investigating, developing and validating the operation, control, protection, safety and telecommunication infrastructure of microgrids [84]. The *More microgrids* project includes several aims such as standardisation and benchmarking, study of the impact on the operation of power system, alternative network designs, etc. [85]. In the same way, the European Technology Platform for Electricity Networks of the Future, also called SmartGrids ETP, was created in 2005 with the general objective of providing a bold programme of research, development and demonstration to meet Europe's future electricity needs [86]. Smart grids and microgrids are included within the research objectives of this organisation. A summary of the microgrids installed all around the world is presented in Tables 5–7 [22,83,87–101].

### 4.2. Rural electrification: off-grid microgrids

Microgrids are connected to the main grid when it works properly. When any abnormal operation is detected in the main

**Table 6**
Examples of microgrids in Asia and Oceania.

| Situation | | Project manager | Type | | Control | | Structure | |
|---|---|---|---|---|---|---|---|---|
| Place | Country | | Real | Test-bed | Cent. | Decen. | AC | DC |
| Newcastle | Australia | CSIRO Energy Center | | √ | √ | | √ | |
| Hefei | China | Hefei University of Technology (HFUT) | √ | √ | | √ | | |
| Tianjin | China | Tianjin university | | √ | √ | | √ | |
| Changwon | Korea | Korea Electrotechnology Research Institute (KERI) | | √ | √ | | √ | |
| Uttar Pradesh | India | Mera Gao Power (MGP) | | √ | √ | | √ | |
| Aichi | Japan | Aichi institute of technology (AIT), NEDO | √ | | | | | |
| Akagi | Japan | NEDO | √ | √ | | √ | | |
| Hachinoche | Japan | NEDO | √ | | √ | | √ | |
| Kyoto Eco-Energy | Japan | NEDO | | √ | √ | | √ | |
| Sendai | Japan | NEDO | √ | | √ | √ | | |

**Table 7**
Examples of microgrids in North America.

| Situation | | Project manager | Type | | Control | | Structure | |
|---|---|---|---|---|---|---|---|---|
| Place | Country | | Real | Test-bed | Cent. | Decen. | AC | DC |
| Boston Bar | Canada | BC Hydro | √ | | | √ | √ | |
| Senneterre | Canada | Hydro Quebec (HQ) | √ | | | √ | √ | |
| Albuquerque, New Mexico | USA | NEDO, Sandia National Laboratories, The University of New Mexico and Japanese companies | | √ | [a] | | [a] | |
| Ansonia, Connecticut | USA | Pareto Energy, Ltd. and Connecticut Center for Advanced Technology (CCAT) | √ | | [a] | | [a] | |
| Borrego Springs, California | USA | San Diego Gas & Electric Company (SDG & E) | √ | | √ | | √ | |
| Columbus | USA | Dolan Technology Center | | √ | | √ | √ | |
| Washington | USA | Howard University | | √ | [a] | | [a] | |
| Chicago | USA | Illinois Institute of Technology | | √ | | √ | [a] | |
| Los Alamos, New Mexico | USA | NEDO | | √ | [a] | | [a] | |
| Madison | USA | University of Wisconsin | | √ | | √ | √ | |
| Marin County, California | USA | Xanthus Consulting International, Infotility, Inc. | √ | | | √ | √ | |
| California | USA | Santa Clara University | | √ | [a] | | √ | |
| Stamford, Connecticut | USA | Pareto Energy | √ | | [a] | | [a] | |
| San Diego | USA | University California San Diego | | √ | [a] | | [a] | |
| Twenty-nine palms, California | USA | General Electric (GE) | √ | | √ | | √ | |

[a] No data found.

**Table 8**
Examples of islanded microgrids all around the world.

| Situation | | | Project manager | Control | | Structure | |
|---|---|---|---|---|---|---|---|
| Region | Place | Country | | Cent. | Decen. | AC | DC |
| Africa | Akkan | Morocco | 2 | √ | | √ | |
| | Diaka Madina | Senegal | 2 | √ | | √ | |
| | Lucingweni | South Africa | National Energy Regulator of South Africa (NERSA) | | √ | √ | √ |
| Antarctic | Princess Elisabeth Station | Antarctic | Laborelec | √ | | √ | |
| Asia | Kuroshima island | Japan | Kyushu Electric Power | √ | | √ | |
| | Miyako island, Okinawa | Japan | Okinawa Electric Power Company (OEPC) | [a] | | [a] | |
| | Town Island | Hong Kong | Hong Kong University (HKU) | √ | | √ | |
| Europe | Kythnos | Greece | | √ | | √ | |
| North America | Bella Cola | Canada | BC Hydro, GE, PowerTech | √ | | √ | |
| | Hartley Bay | Canada | Pulse Energy (ICE) | | √ | √ | |
| | Kasabonika Lake | Canada | Hydro One, GE, University of Waterloo | √ | | √ | |
| | Nemiah Valley | Canada | NRCan | √ | | √ | |
| | Ramea Island | Canada | N & L Hydro, Nalcor Energy, NRCan, Frontier Power | √ | | √ | |
| | Colonias, Texas | USA | Texas State Energy Conservation Office (SECO), Texas Engineering Experiment Station, Xtreme Power | √ | | √ | |
| | Fort Bragg, North Caroline | USA | Encorp, Honeywell | √ | | √ | |
| Oceania | Kings Canyon | Australia | UNSW (Sydney) | √ | | √ | |
| South America | Chico Mendes | Brazil | Eletrobas | √ | | √ | √ |
| | Ilha da Ferradura | Brazil | [a] | √ | | √ | |

[a] No data found.

grid, the microgrid is disconnected and it begins to work in islanded mode. Despite the fact that they do not satisfy the microgrid definition, there are several projects all around the world that include islanded microgrids. These microgrids have no connection to the main grid but are able to supply remote places cleanly and efficiently. For example, in the Antarctic, the Princess Elisabeth Research Station is supplied by an islanded grid based on solely renewable energies [102]. Some examples are also found in Town Island (Hong Kong) [103], Kings Canyon (Australia) [83] and Hartley-Bay, Ramea island, Bella Cola and Kasabonika Lake (Canada) [87]. In addition, most developing countries include rural electrification policies in their socio-political development efforts in which off-grid microgrids are gaining special attention. Several government-led rural electrification programmes have been implemented worldwide. For example, in remote areas of the Amazon in Brazil, such as Chico Mendes and Ilha da Ferradura, grid electrification has been in part replaced by decentralised electricity supply alternatives [104]. Several islanded grids can be also found in Africa in villages such as Lucingweni (South Africa), Diaka Madina (Senegal) and Akkan (Marrocco) [105–107]. Some examples of off-grid microgrids are presented in Table 8 [87,102–105,108–111].

### 4.3. Future research into microgrids

Microgrids have attracted the interest of the scientific community over recent years. However, there are still a number of gaps in the technical aspects that require the attention of researchers [3,29,31,112]:

- *DC microgrids*. Several advantages such as nonreactive power flow on lines, no need for synchronisation, reduced losses, etc. are achieved when a DC distribution system is chosen instead of an AC system. However, this technology is not mature enough and still needs more research efforts in order to take advantage of DC systems.
- *Protection of microgrids*. Traditional protection systems for traditional grids must be adapted to microgrids because of their inherent characteristics such as the variability of DERs, power rate limits, dual-mode operation, etc. Standards that define the protection issues for microgrids should be implemented in order to achieve a suitable design of their protection scheme.
- *Optimal operation*. Microgrids have to satisfy multiple performance criteria in order to guarantee optimal operation. Several functions and tasks are involved in this aspect such as load management, energy optimisation, etc. Microgrids have to dispatch or coordinate the DGs and SS units properly in order to balance the demanded and generated power that can be both electrical and thermal as in combined heat and power (CHP) systems. A number of research projects deal with some of these tasks, as indicated in Section 3. However, research efforts are still needed in order to fulfil all the requirements needed for the optimal operation of microgrids.

## 5. Conclusions

Microgrids have been presented as an attractive option for integrating DERs into the main grid. Thus, several institutions and enterprises all over the world are focusing their research programmes on microgrids. Due to this extensive research, several control systems have been proposed in the literature. Among the designed transmission systems, the interest in DC microgrids is increasing over recent years due to the advantages they offer in comparison with AC microgrids. On the other hand, both centralised and decentralised hierarchical controls for microgrids have been presented as the preferred candidates for microgrids. The MAS decentralised control offers several advantages, the most important of which include its *plug* & *play* capability. Its features make the decentralised control most suitable in cases of microsources belonging to different owners, microgrids operating on the market, etc. Likewise, the easy implementation and the global perspective of the system obtained with the centralised control make this control more suitable in cases of small-scale microgrids, microgrids with microsources with common goals, etc.

Research into microgrids has been extended all over the world. In this way, several countries such as Canada, Japan and USA are engaged in several research projects dealing with microgrids. Among the experimental microgrids studied, it has been shown that most of the microgrids implemented use AC transmission systems with centralised controls. It has been also seen that islanded microgrids play an important role in rural electrification projects all over the world. Finally, a number of issues such as circuit protections, DC distribution systems and optimal operation of the whole system still require a great deal of dedicated research in order to guarantee a suitable development of microgrids in the future.

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